Development of Delta-Blade Wind Turbines

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Foreword

Since 1976, numerous projects have been initiated in Alberta by industry and by academic research institutions which are aimed at better utilization of Alberta's energy resources.

These research, development and demonstration efforts were funded by the Alberta/Canada Energy Resources Research Fund (A/CERRF), which was established as a result of the 1974 agreement on oil prices between the federal government and the producing provinces.

Responsibility for applying and administering the fund rests with the A/CERRF Committee, made up of senior Alberta and federal government officials.

A/CERRF program priorities have focused on coal, energy conservation and renewable energy and conventional energy resources. Administration for the program is provided by staff within the Scientific and Engineering Services and Research Division of Alberta Energy.

In order to make research results available to industry and others who can use the information, highlights of studies are reported in a series of technology transfer booklets. For more information about other publications in the series, please refer to page 10.

Development of Delta-Blade Wind Turbines

The coastlines of Canada and the southern regions of the three prairie provinces are among the windiest areas of the country. According to meteorological records, winds in southern Alberta are always present, averaging speeds of more than 3.6 m/s (8 mph) 353 days of the year. At more than 23 meteorological stations located across the country, the measured energy available from winds exceeds 2 000 kWh/m^2 a year, which demonstrates that Canada has one of the highest wind regimes in the world. This makes wind energy a substantial renewable resource simply waiting to be tapped.

While various types of small wind turbines have been used throughout the world for decades — or centuries in some places — little progress has occurred in Canada with using wind turbines, except to pump water for livestock. Although wind turbine use increased during the 1970s because of rising fuel prices, and some electricity-generating units have been tried in isolated experiments across the country, little has been done to tap the opportunities available from the use of large, low-cost and efficient wind turbines designed especially to pump large volumes of water.

For many years, it has been suggested that such opportunities exist in drought-prone southern Alberta, where the steady winds prevailing in the region could be used to pump water into the irrigation systems that are needed for crop production.

In the late 1970s, a new wind turbine concept, originating at the University of Calgary, showed great promise of becoming a low-cost wind energy system, but first it was necessary to build and demonstrate it on a large scale. The development of this technology, and its evolution from laboratory-scale models to a full-scale prototype, was financed in part by A/CERRF from 1981 to 1986.

A Large Delta-Blade Wind Turbine: An Alberta Development

Historically, wind turbines have suffered from the disadvantage of having high capital costs for each unit of output. During the 1970s, however, Drs. J.A.C. Kentfield and D.H. Norrie of the University of Calgary suggested a concept that might be used to lower capital costs without reducing the wind turbine's rotor efficiency.

Kentfield and Norrie presented a paper at the 1977 Miami International Conference on Alternative Energy Sources, in which they described a delta-wing turbine design using simple-to-build flat plate blades. These "planform" blades can be made from steel, but plywood or simple fabric-covered frames could be used, making the technology more amenable to Third World construction methods.

The design further uses low rotor speeds to avoid rotor stress, and achieves maximum torque when the rotor is not moving (zero speed). This allows the unit to start under load without needing a clutch. These two features are suitable for direct water pumping, whereas high-speed, low-torque rotors are more suitable for generating electricity.

Wind tunnel studies of small wind turbines, having a rotor diameter of 394 mm (15.5 in), showed that an eight-blade configuration of flat blades with a simple flap attached to each blade's trailing edge was a promising design. Maximum efficiency was found to be 55 per cent and the torque coefficient at zero speed was 0.6.

In 1978, a Calgary firm, Abacus Engineering and Machine Ltd. (now ABAX Energy Services Ltd.), agreed to build and test large-scale wind turbines based on the Kentfield-Norrie design.

Wind Turbine Components

Wind energy conversion systems (sometimes called WECS) comprise six basic components. They are: rotor, control mechanism, power transfer mechanism, conversion device, tower and storage system.

Rotor performance is a measure of the rotor's ability to convert wind energy to mechanical energy at the rotor shaft. It is usually expressed in terms of "power coefficient." The mechanical energy produced by the rotor must be transferred to the equipment that will be operated by the wind turbine. This is accomplished by using power transfer devices such as chains, gears or V-belts. Conversion devices, such as pumps and generators, transform the mechanical energy into potential energy, electrical energy or heat. In most applications, arrangements must be made to temporarily store the transformed energy before it can be used. This is done using storage devices such as batteries, heated fluids or water that has been pumped to an elevated storage location.

Because higher wind speeds are generally found at greater elevations above the earth's surface, WECS usually are mounted on tall support towers, which also provide adequate ground clearance to reduce the effect of wind turbulence caused by local obstructions.

Also included in WECS is a mechanism to control starting, stopping and overspeed furling of blades, as well as provide fail-safe protection against very high wind speeds.

The power output of wind turbines can be calculated from the expression:

$$P = \tfrac{1}{2} K\rho AU^3$$

where

P = power output

ρ = air density

A = projected area of the rotor

U = wind speed at the rotor

K = constant

Power output, therefore, is directly proportional to the air density and the rotor area and, because it is proportional to the cube of the wind speed, is very sensitive to wind velocity.

Delta-Blade Design Features

From the beginning, the Kentfield-Norrie delta-blade wind turbine was designed to pump water directly, rather than generate electricity, and it was meant to operate over a broader range of wind speeds than do other types of wind turbines. For example, most commercially available wind pumps have a low power output (less than 0.5 kW) and are designed to operate best over a narrow range of wind speeds, usually between 6 and 7 m/s (13 to 16 mph). Conversely, small wind generators usually are designed to operate from 9 to 12 m/s (20 to 27 mph) and are capable of a wide range of output (from 0.1 to 10 kW).

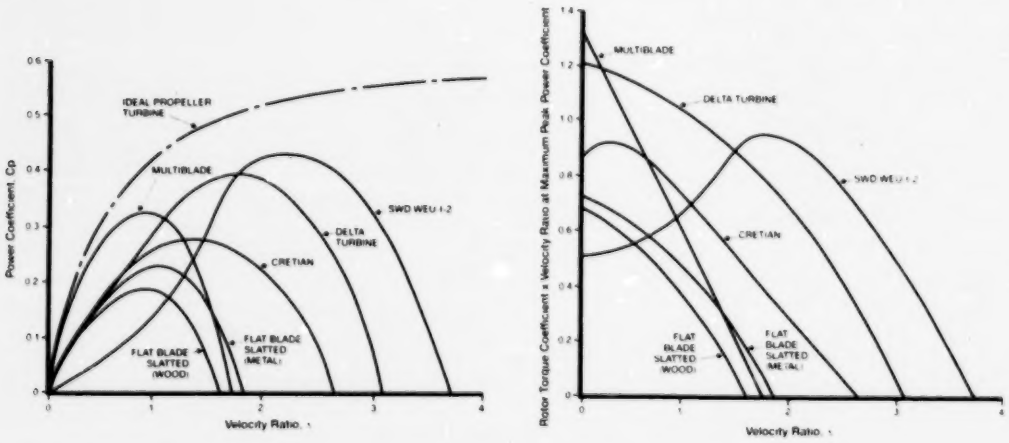
In contrast, the Kentfield-Norrie design was intended to capture energy throughout the normal range of wind speeds and provide greater energy output through a variable capacity pumping system. This involved a pump stroke control mechanism that would double the effective power output of the turbine as compared to the output available from a fixed stroke system. The variable stroke mechanism is designed to adjust the pump stroke over a ratio of 16:1 to ensure maximum efficiency of the wind turbine over a wind speed range of 3.3 to 13 m/s (7.5 to 30 mph). Calculations showed the variable stroke mechanism should increase the average seasonal output of pumped water in southern Alberta by 80 per cent over the same turbine without a variable stroke system.

Commercial Development

After ABAX became involved, it was decided that a prototype having a rotor diameter of 22.8 m (75 ft) should be built and its performance, reliability, costs and benefits would be determined under typical water-pumping conditions. As the engineering aspects of the project evolved, potential markets for delta-blade turbines were assessed, especially in Alberta, and appropriate economic considerations were investigated.

An eight-bladed delta turbine having a rotor diameter of 3.3 m (10.8 ft) was tested at the National Research Council wind tunnel in Ottawa, and power coefficient results (after confirmation by further model tests) were compared with existing commercial-scale wind turbines.

Power Coefficient versus Velocity Ratio (left) and Torque Characteristics (right) of 3 to 4 m rotor diameter wind turbines.



(Source: Delta Windpump Corporation)

Plots of power coefficient versus velocity ratio showed the peak power coefficient of the delta-blade turbine is 25 per cent higher than that produced by the classical multi-bladed turbine commonly used on North American farms to pump water.

When the torque characteristics of these same turbines were compared, thus eliminating any possible effects caused by differing rotor speeds, the delta-blade turbine was found to be essentially equal to the traditional multi-bladed turbine. These results suggested that the technical aspects of the design were competitive with existing designs, and the market survey confirmed that the winds of southern Alberta possess sufficient potential energy to justify commercial development of the turbine.

Potential Applications

The most promising applications for the machine in southern Alberta were seen to be: (1) as a means of pumping large quantities of water for irrigation systems and; (2) to pump water into storage reservoirs associated with hydroelectric power generation.

Investigations revealed that approximately 405 000 hectares (one million acres) of farmland in southern Alberta are currently under some form of irrigation, and it is expected this area will increase by at least 50 per cent in the foreseeable future, with a substantial increase in the need for pumping systems.

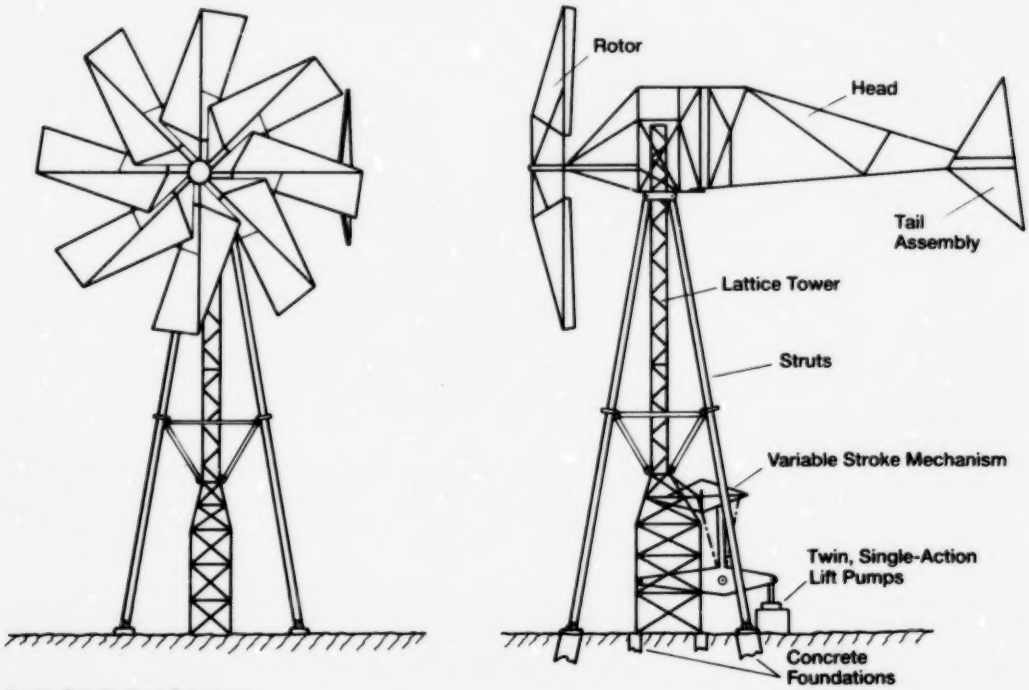
Analysis of existing hydroelectric generating plants in Alberta showed that using the delta-blade turbine to recirculate downstream water to an upstream storage area, so that it could be used again in the hydroturbines, would allow plants to generate more electricity during a given period. It also would add more flexibility to the water storage and release aspects of the operation.

Other potential uses of the turbine include: supplying water for recreational use, draining sloughs to reclaim land for agricultural purposes and creating wetlands for waterfowl. In each of these applications, large volumes of water must be pumped, often involving locations remote from existing power lines.

Economic Assessment

The preliminary economic analysis indicated that the turbine could be cost-competitive with water pumps powered by electricity or driven by engines that were fuelled by natural gas, diesel or propane. Furthermore, it was estimated that the turbine should last at least 30 years (perhaps as long as 60 years), which enhances its economic advantages when compared with alternative water pumping

Delta-Blade Wind Turbine Configuration



(Source: Delta Windpump Corporation)

methods. Features such as slow operating speed, sealed bearings and simple operating controls were expected to contribute to its long service life.

Prototype Development

Initially, ABAX designed a full-scale prototype turbine having a rotor diameter of 22.8 m (75 ft), but to reduce development costs, the unit that was eventually built was scaled back to a rotor diameter of 16 m (50 ft). This machine, designated the WP-50, has eight major welded steel components.

1. A steel lattice *tower* that can be supported with struts or cables. It allows the top assembly, or head, to be either self-erected in remote locations or hoisted by a large crane.
2. Cast-in-place concrete *foundations* to support the tower, struts or cables.
3. A *head*, which is a steel structure that holds the rotor shaft, rocker arm and tail assembly. It can swivel freely on the tower using roller bearings.
4. A delta-blade *rotor* mounted at 31.4 m (103 ft) above ground.
5. A *tail* assembly supported by the head. The tail axis and the rotor axis are offset from each other, but are usually kept parallel by a counterweight system. Under high wind conditions, the rotor and tail will cease to be aligned and furling will occur.
6. A *variable stroke mechanism* near ground level is connected to the rotor shaft for automatic operation. It monitors the speed of the rotor and automatically adjusts the pump stroke to yield maximum output from the turbine.
7. Twin, single-action *lift pumps* driven by a pump rod from the variable stroke mechanism.
8. A *water intake sump*, which connects the lower portion of the pump cylinder to a water source.

Certain elements of the design have been patented.

Structural analysis of the design showed that stress levels could be kept below acceptable fatigue limits and the WP-50 was capable of accommodating the most critical cases of loading. It should also survive winds gusting to 260 km/h (163 mph). It could readily be fabricated from steel available in Alberta, and construction of the rotor blades should be simple because they are flat.

WP-50: Head assembly being lifted into place.
(Source: Abax Energy Services Ltd.)

Lower drive system of WP-50, showing rocker arm, variable stroke mechanism and remote drive.
(Source: Abax Energy Services Ltd.)

Comparison of Wind Turbines

Before a prototype unit was built, an independent study was undertaken in 1981-1982 by the Dalcor Group in Edmonton to compare the WP-50 with other commercially available wind turbines.

Because one of the most important uses for wind turbines in Alberta is to pump water for irrigation, either directly or indirectly by first generating the electricity needed by an electrical water pump, the ABAX WP-50 and four aerogenerators were evaluated on their theoretical ability to perform the following task:

> **to continuously pump water at 1.4 m^3/sec (50 ft^3/sec) from a natural reservoir (Lost Lake) to an irrigation canal, at a head of 9.1 m (30 ft) during the irrigation season (May 1 to October 31).**

The four commercially available aerogenerators were manufactured by:

1. Boeing Engineering and Construction Company (Model MDD-2);
2. United Technologies Hamilton Standard (Model WTS-4);
3. WTG Energy Systems Incorporated (Model MP-200); and
4. DAF-Indal Limited (Darrieus).

Because the performance data supplied by these four manufacturers were not directly relevant to the test conditions (in contrast to the detailed information supplied by ABAX), Dalcor calculated the missing information based on principles of wind energy conversion. Also, the wind regime at Lost Lake was assumed to be the same as at Lethbridge, where the nearest meteorological station is located.

The expected energy production for each machine was calculated by first determining the ideal Betz limit, which is the maximum amount of energy that can be recovered by an ideal wind turbine. Once the Betz limit was known, corrections were made (based on field experience from other studies) to determine the expected annual energy production from actual, rather than ideal, wind turbines.

After calculating the water-pumping load needed for a six-month irrigation season, and comparing the energy requirements with the potential energy production by each wind turbine, it was concluded that a single Boeing or Hamilton Standard wind turbine would be adequate to supply peak demand electricity for the six-month period, but clusters of each of the other wind turbines would be required to provide the same amount of energy. Thus, the task required five WTG, five DAF-Indal and three ABAX wind turbines.

In calculating the economic benefits of each wind turbine, it was assumed that any electricity generated in excess of the six-month requirements could be transferred to the existing electricity distribution grid.

Using a formula that considered factors such as capital costs, operating and maintenance costs and energy production, an equivalent cost of energy in dollars per kilowatt-hour was calculated at 15 to 20 per cent capital recovery rates over 20- or 30-year amortization periods for each brand of wind turbine. The comparison revealed that:

1. the cluster of three ABAX wind turbines was marginally more economic than the other systems after operating for six months. The economics are even better on an annual basis;
2. it costs more to produce electricity with wind turbines than with the current Alberta method of coal-fired generating stations. However, costs can be more competitive in remote areas that are not served by power lines.

In North America, wind-generated electricity supplied to a power grid must be produced at a synchronous frequency of 60 Hz. To achieve this requirement, most wind turbines use complex variable speed and constant frequency controls. The control system proposed for the ABAX wind turbine, however, appears to be simpler and is designed to react mechanically to changing wind conditions. This is regarded as a major technical advantage. Another positive feature of the ABAX is its low rotational rotor speed, which should lead to fewer component failures.

The Dalcor investigators concluded that the ABAX wind turbine offers significant cost advantages when operated year-round. Therefore, it should be considered for remote site applications or be used in conjunction with hydroelectric dams to pump downstream water back to the reservoir.

Performance Testing

By August 1983, the WP-50 prototype had been fabricated, shop-tested and erected at the ABAX plant site in Calgary. A detailed procedure for instrumenting and testing the prototype was prepared in co-operation with the Alberta Research Council and the National Research Council, Division of Energy.

Meanwhile, a new company, Deltx Windpump Corporation, was established to market ABAX-built wind turbines, now referred to as Deltx products.

Over a two-year test period, the WP-50 was operated for hundreds of hours and individual components were bench-operated for thousands of hours.

Annual Cost of Energy * ($/kWh)

Manufacturer	BOEING	HAMILTON STANDARD	WTG ENERGY	DAF-INDAL	DELTX (ABAX)
Peak Energy Demand					
a. 15%; 20 years	0.1789	0.1196	0.1895	0.1307	0.1115
b. 15%; 30 years	0.1702	0.1136	0.1805	0.1244	0.1065
c. 20%; 20 years	0.2323	0.1561	0.2445	0.1692	0.1421
d. 20%; 30 years	0.2270	0.1525	0.2391	0.1654	0.1390

*** The cost of energy ($/kWh) applied in this comparison is determined by the formula:**

$$COE = \frac{[(CC \times CRF) + O\&M - (E_0 \times R_0)]}{E \times AF}$$

where:

COE = **Annual Cost of Energy ($/kWh)**
CC = **Installed Capital Cost ($)**
CRF = **Capital Recovery Factor (%)**
O & M = **Annual Operating and Maintenance Cost ($/yr)**
E_0 = **Energy Supplied to Grid During the Year (kWh)**
R_0 = **TransAlta Utilities Payment Rate for Energy Supply to Grid ($/kWh)**
E = **Total Energy Produced Annually by Wind Machine (kWh)**
AF = **Availability Factor (%)**

(Source: Comparison Study of Wind Turbines, The Dalcor Group, April 1982)

As might be expected in a new product, some components required modifications, but the first test of the prototype demonstrated its technical viability. It cleared the way for a comprehensive, fully instrumented performance test program, which was undertaken to establish the turbine's performance curve and to verify actual aerodynamic characteristics versus those predicted by theory. As well, the physical integrity of various components was measured and the performance of the variable stroke mechanism was determined.

From March 18 to May 17, 1986, performance testing of the Deltx WP-50 was carried out by DRB Engineering Consultants Ltd. using an automated data logging system to collect information on:

- wind speed and direction at hub height;
- ambient temperature;
- atmospheric pressure;
- turbine rotor rotational speed;
- rotor yaw error;
- pump stroke length;
- water flow rate;
- pumping head; and
- rotor power output.

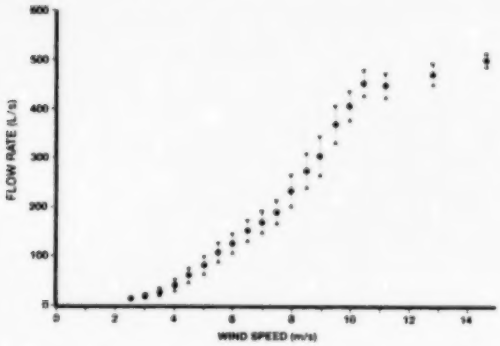
Each of these parameters was measured every second; one-minute averages were stored on magnetic tape for analysis. Only those data collected when the tip speed ratio was between 1.25 and 2.40 were analysed.

The data showed that the peak system power coefficient (Cp) was 0.31 at a tip speed ratio of 1.9. This value corresponded to a predicted Cp of 0.34 at a tip speed ratio of 1.65. The rotor Cp equalled the predicted value of 0.41.

At 10 m/s (22 mph), the variable stroke mechanism reached the end of its range of movement. This was unexpected and prevented performance measurements at higher wind speeds. Nevertheless, the WP-50 closely approximated its predicted performance at wind speeds up to 10 m/s (22 mph) and began pumping water at a 4.9-m (16-ft) head when the wind speed was 2.2 m/s (5 mph). At a wind speed of 15 m/s (33 mph) and a pumping head of 6.3 m (20.7 ft), the water-pumping rate reached 500 L/s (110 Imperial gal/s).

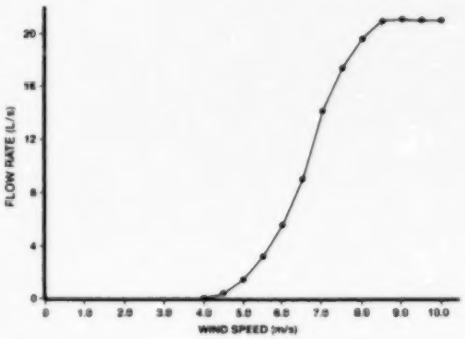
Because the pump stroke length controller was unable to increase the pump stroke at wind speeds above 10 m/s (22 mph), it was concluded that the method of transferring power from the rotor to the pumps should be reassessed. Subsequently, an hydraulic power transfer system was designed.

WP-50: Flow Rate vs Wind Speed
March 18 - May 17, 1986



(Source: *Performance Test Results of the Deltx WP-50 Windpump Prototype*, DRB Engineering Consultants Ltd., September 1986)

WP-20 Performance



(Source: DRB Engineering Consultants Ltd.)

The project demonstrated that the delta-blade concept is appropriate for Alberta's wind conditions. It substantiated the original performance calculations and it showed that the design represents an improvement over other currently available wind turbines.

Based on the WP-50 design, a smaller wind pump, the WP-20, was built and marketed commercially by Deltx Windpump Corporation.

This unit, which has a rotor diameter of 5.0 m (16.5 ft) and uses either a fixed stroke mechanical system or an hydraulic power transfer mechanism, underwent performance testing by DRB Engineering Consultants Ltd.

Tests were performed at the Lethbridge Wind Research Site, where the water-pumping characteristics of the fixed-stroke mechanical version of the WP-20 were measured.

At a 6.1-m (20-ft) lift, the WP-20 cut in when the wind speed reached 4.2 m/s (9.2 mph) and achieved a maximum pumping rate of 21 L/s (4.7 gal/s) at 8.6 m/s (19 mph). Indications from this limited test showed that the WP-20's water-pumping performance was better than any of the 14 conventional multi-bladed water-pumping wind turbines previously tested.

Advantages

The WP-50 and WP-20 delta-blade wind turbines offer the following advantages when compared with alternative water-pumping systems.

- They are self-starting, even under load.
- Their slow rotor speed means low noise levels.
- They do not require the use of sophisticated, highly stressed blades.
- They are expected to have a long lifetime with minimal maintenance.
- They can perform throughout a broad range of wind speeds.
- They can outperform conventional multi-bladed wind turbines.
- They are cost competitive with other water-pumping systems, especially in remote locations.
- Their use removes some of the uncertainty about long-term energy costs.

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